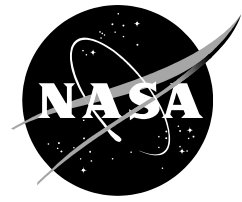


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High Temperature Thermoplastic Additive Manufacturing Using Low-Cost, Open-Source Hardware

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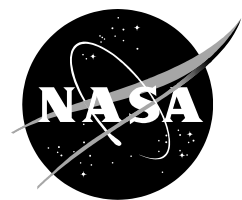
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Introduction

Additive manufacturing (or 3D printing) via Fused Filament Fabrication (FFF), also known as Fused Deposition Modeling (FDM), is a process where material is placed in specific locations layer-by-layer to create a complete part. Printers designed for FFF build parts by extruding a thermoplastic filament from a nozzle in a predetermined path [1]. Originally developed for commercial printers, 3D printing via FFF has become accessible to a much larger community of users since the introduction of RepRap printers [2]. These low-cost, desktop machines are typically used to print prototype parts or novelty items [3]. As the adoption of desktop sized 3D printers broadens, there is increased demand for these machines to produce functional parts that can withstand harsher conditions such as high temperature and mechanical loads [4, 5]. Materials meeting these requirements tend to possess better mechanical properties and higher glass transition temperatures (T_g), thus requiring printers with high temperature printing capability [6]. Additional print environment specifications are needed in order to produce quality parts with these high temperature materials. The most critical of these specifications is maintaining a high part temperature, preferably at or near the T_g of the material, during the printing process. Doing so reduces the amount of warping that occurs in the part during printing and facilitates interlaminar adhesion between the print layers [7]. Without these environmental conditions, the high temperature 3D printed parts will be functionally limited or useless. Additionally, these materials require extrusion temperatures upwards of 400°C [6]. While industrial machines (e.g., Stratasys Fortus 450mc) are equipped to print a wide variety of materials with high T_g s such as polyetherimides (PEI or Ultem®) [8], desktop sized printers are limited to lower temperature filaments such as polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS) [9]. Currently, there are very few desktop printers with the advertised capability of high temperature thermoplastic printing [4, 10, 11]. Most desktop 3D printers are not designed to maintain the necessary environment to sustain the proper part temperature during the printing process and/or the printer components cannot withstand the elevated temperatures required during printing. A system has been developed based on a commercially available desktop 3D printer that is capable of producing high quality, warp-free parts from high temperature thermoplastics. This report outlines the problems and solutions, and includes a detailed description of the machine design, printing parameters, and processes specific to high temperature thermoplastic 3D printing.

Abbreviations

ABS	Acrylonitrile Butadiene Styrene
FDM	Fused Deposition Modeling
FFF	Fused Filament Fabrication
IR	Infrared
PC	Polycarbonate
PEI	Polyetherimide
PLA	Polylactic acid
T_g	Glass Transition Temperature

Printer Development

Design Specifications

As described above, a central challenge to high temperature printing is maintaining the part temperature during printing. To accomplish this, industrial machines employ a convection oven around the build volume of the printer to maintain the proper build environment [12]. This is not a practical solution on desktop machines for a variety of reasons, including the overall dimensions of the machine and the design of the gantry and extruder systems. Therefore, the system developed and described herein uses directed infrared (IR) heating to focus energy on and control the temperature of only a printed part rather than the entire machine. Doing so keeps the printing environment at a low enough temperature for many of the machine components to maintain structural integrity and function properly. However, some stock components such as electronics, stepper motors, ABS printed machine parts, and hot ends still required modification to ensure survivability and compatibility with the elevated temperatures the machine is exposed to during printing.

Machine Design

Starting with the stock Lulzbot Taz 4 3D printer (Aleph Objects, Loveland, CO) (Figure 1a), a number of modifications were made to enable high temperature thermoplastic printing (Figure 1b). These modifications are described in detail below.

Electronics and Machine Enclosure

An enclosure system was constructed around the machine in order to retain heat and prevent drafts from affecting the printed part. The enclosure consisted of an aluminum frame with cardboard foam core side walls, and included a door and window for machine access and viewing while the printer is operating. A rubber seal was placed around the door to prevent heat loss. Figures 2a and 2b show a model of the printer enclosure. Figure 2c shows the as-built enclosure without the front window installed. To avoid overheating the control board (Rambo v1.2), the electronics box normally attached to the side of the printer was removed and placed outside of the enclosure. Cabling was routed through the sidewall of the printer and the lengths of the wires were adjusted where needed. Figure 3 shows this set-up.

Printer Part Material Upgrades

The base machine contains many printed parts built from ABS. The T_g of this material ranges from 85 to 110°C, which is lower than the temperature the parts may be subjected to during high temperature printing. To prevent warping or failure of the ABS parts in the enclosure, all parts made from ABS were replaced with parts made from a material with a higher T_g : initially, polycarbonate (PC) ($T_g = 147^\circ\text{C}$). Since PC is susceptible to stress cracking when exposed to hydrocarbons, the PC parts were eventually replaced with Ultem® ($T_g = 218^\circ\text{C}$) parts printed on the machine.

High Temperature Hot End

During printing, filament is deposited onto the print bed using the cold end to apply pressure and push the material through the hot end where it is heated and extruded through a small nozzle. The locations of the hot end and cold end are shown in Figure 4. The stock hot end (nozzle) on the machine is only rated for 300°C due to limitations of the thermistor as well

as the ABS cold end. This is below the required temperature for most high temperature materials. Therefore, a new hot end (E3D-v6 1.75 mm Universal, E3D, Oxfordshire, UK) was purchased and installed that allows for temperatures above 400°C. The kit included the nozzle, heat sink, thermal break, and fan shroud that were used in the modified machine. In addition, a 24V fan (for compatibility with the existing electronics) and 500°C thermistor (B3 Innovations, Cleveland, OH) were purchased separately and installed on the machine. No modifications were needed to integrate the new thermistor and fan into the E3D hot end. A counter-bored hole was added to the cold end mount to allow the hot end to sit flush with the cold end. The 2 mm inner diameter tubing included with the kit was installed per the instructions and then cut flush with the top of the hot end.

IR Heating Lamps

Maintaining part temperature during printing is critical to a successful print. Therefore, twelve 35 W halogen light bulbs (Sunlite, Brooklyn, NY) were installed surrounding the build volume. Figure 5 shows the arrangement of the lights in the machine. Because the build platform moves in the y-direction during the print, the lights were arranged to ensure ample coverage of the part regardless of the position of the y-axis. The angle of the lamp relative to the y-axis was staggered by 12 degrees starting perpendicular to the y-axis and going towards the center of the machine. Four brackets each holding three lamps were hard mounted to the machine frame. Figure 6 shows the lamps mounted in the machine.

Stepper Motor Coolers

Linear movement of the machine is accomplished using stepper motors. There are at least five stepper motors installed on the machine that have a maximum service temperature of 55°C. The typical air temperature of the enclosure is around 62°C. Complications such as missed steps, wear, and total failure of the motor will result if the motors are run above their maximum service temperature. Active cooling using forced air convection was added to the system to prevent these issues. A cooling shroud was designed to direct the air flow around the outside of the motor. It was installed around each of the motors and sealed using high temperature silicone (VersaChem Mega Copper Silicone, ITW Consumer, Hartford, CT) (Figures 7a and 7b). Figure 7c shows the cooling shroud used in the prototype system and points out the flow channel for directing air around the motor. The design of the cooling shroud was tailored to the dimensions of the stepper motor. Figure 8 shows the pneumatic schematic of the cooling system. A single pressurized air line is fed into the system and then distributed among all of the motors. The exhaust from the cooling shrouds is then fed back outside the enclosure and released into the environment. Input pressure (90 psi max) is adjusted to ensure sufficient cooling.

Filament Storage

Some printing materials are known to be hygroscopic, which can cause porosity issues during printing. When a filament with adsorbed moisture is used for printing, trapped water vapor forms bubbles during extrusion from the hot end. To prevent this, a special filament box (Filabot, Barre, VT) with desiccant added to keep the humidity at around 15-20% was used to store the filament. Through-wall connectors and polytetrafluoroethylene tubing were used to provide a path for the filament to travel from the filament box into the enclosure and then to the cold end without being exposed to the ambient environment. Figures 9a and 9b show the filament box and guide tube.

Electronics

Additional electronics were required to power the IR heating lamps installed on the machine. The IR heating lamp electronics were independent of the control board because of the high load requirements. Figure 10 shows the schematic of the enclosure lamp electronics. Standard outlet electrical power (120VAC 60Hz) was fed into a power bus and split into two separate lines. These lines were then routed through a solid state relay and into another power bus where they were split an additional six times and each routed to a lamp. Power and logic for the relays were supplied by the control board via expansion pins. As with the control board, the relays and power bus were located outside of the enclosure as shown in Figure 3. All lamp power was fed to a common ground.

Firmware

Changes were made to several files of the firmware (Marlin) so that the new modified printer would function properly. The maximum allowable hot end temperature was changed in “configuration.h” from 300°C to 500°C to reflect the new high temperature configuration. A new temperature table was added to “thermistortables.h” to allow the controller to interpret the readings from the 500°C thermistor. Two machine commands were added to “marlin_main.cpp” in the form of M codes (M740 and M741) to turn the IR heating lamps on and off when required. The process was written with a 0.5 s delay between the actuation of each relay as a safety measure to prevent the circuit from becoming overloaded. The new pins for operating the relays were added to “pins.h” and defined in “marlin_main.cpp”.

Printing Parameters

Printing parameters for a given material can vary depending upon factors such as part geometry and machine-to-machine variations. Some general printing parameters for Ultem® 1010 were developed and are listed in Table 1.

Other Modifications

Additional modifications were made to the base printer for ease of use and to reduce variables in the machine. A four-point conductive pad bed leveling system was added to eliminate the need to manually level the bed. The bed leveling system design from a Lulzbot Taz Mini was used with minor modifications made to the conductive touch pads for clearance purposes. A dual nozzle system was also utilized on the machine to allow for multi-material printing. All high temperature printing and bed leveling were done using the forward most nozzle.

Printing Process

A step-by-step guide to printing high temperature materials is described below. Individual steps and the sequence in which they are carried out will vary depending on the machine, printing environment, and material. Parts using the procedure below were printed with Ultem® 1010, 1.75 mm diameter filament purchased from Stratasys (Eden Prairie, MN).

1. Remove a length of filament from its original container and transfer it onto a new spool capable of withstanding temperatures of at least 161°C. A cardboard spool with a metal core is a suitable choice.
2. Place the filament in a convection oven at 161°C for one hour to remove surface adsorbed moisture.

3. Apply a thin layer (3-4 passes) of Elmer's Disappearing Purple® glue stick (Westerville, OH) directly onto the glass print bed.
4. Pre-heat bed to print temperature ($>162^{\circ}\text{C}$). It is recommended that this step be completed while the material is in the oven, as the bed can take >15 minutes to reach temperature.
5. Begin heating the nozzle to print temperature ($345\text{--}375^{\circ}\text{C}$).
6. Once the filament has dried, remove it from the oven while still hot and load it into the printer. Allow a bit of material to extrude from the nozzle.
7. Remove the excess material from the nozzle and cool the nozzle to about 200°C . While cooling, scrub the nozzle with a wire brush until the temperature reaches about 260°C . This will remove any residual Ultem® 1010 on the nozzle and prevent a meniscus from forming at the nozzle outlet which could lead to bed leveling errors.
8. Perform the homing and bed leveling procedures.
9. Load desired g-code and begin the print.
10. At the completion of the print, remove the part from the bed using a spatula or other thin, flat tool. The bed may be allowed to cool to near ambient temperature before the part is removed to ensure even cooling throughout the part. Note however that doing so will make the part more difficult to remove from the bed.

Some modifications to the machine readable code (g-code) that are necessary to ensure a successful print are described below. Ultem® 1010 tends to ooze from the nozzle while at temperature, so a nozzle priming step (20 mm) is added before the first line is printed. Commands are added for turning the lamps on at the beginning of the print and then off at the end. The print bed temperature on the machine runs a few degrees below the set point, so the bed temperature is removed from the g-code and set prior to starting the print (Step 4). All other parameters (e.g. nozzle temperature, print speed, etc.) are controlled through normal means in the g-code. Steps 7 and 8 are performed by the user in this procedure, but could be automated with a few modifications to the machine.

Design Validation and Discussion

As an initial test to determine the effectiveness of the modifications made to the system, functional parts with a variety of dimensions and geometries were printed with Ultem® 1010. Figure 11 shows a comparison of an Ultem® 1010 part printed with and without the IR heating lamps and enclosure system. The parts printed without the IR heating lamps showed significant print quality issues with interlayer adhesion (Figure 11a) and warping (Figure 11b). Multiple attempts were needed to print each part as they often became detached from the build plate during printing. These issues were significantly reduced or eliminated when the IR heating lamps and enclosure were employed. Figures 11c and 11d show these parts. No delamination was present in the printed parts. Additionally, no warping was observed at the edges of the parts.

Some general observations were made on the effect of printing parameters on part quality. Utilizing lower nozzle temperatures typically led to more dimensionally accurate prints. Higher bed temperatures resulted in a further reduction of warping, but at the cost of increased start-up time to allow the bed to reach temperature. The effects of these parameters on parts printed from Ultem® 1010 are consistent with the effects of these parameters on lower temperature materials.

Summary

The necessary modifications, processes, and procedures for printing high temperature thermoplastic materials using low cost, open source hardware were described. The process was demonstrated using an Ultem® 1010 material system and was shown to produce large printed parts with no evidence of warping or delamination. While the system used a Lulzbot Taz machine as the base printer, the modifications described are not unique to this machine type and could be implemented on other low-cost 3D printer systems.

The use of trade names or manufacturers does not constitute an official endorsement of such products or manufacturers, either expressed or implied, by the National Aeronautics and Space Administration.

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Figures and Tables

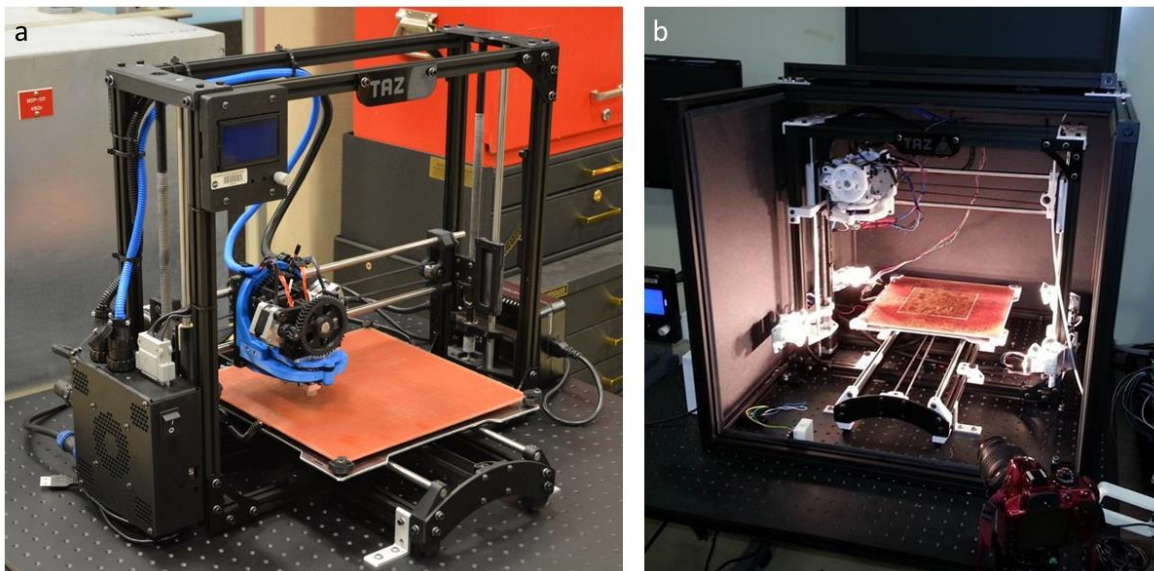


Figure 1: (a) Stock Lulzbot Taz 3D printer. (b) Printer after high temperature modifications. Image Credit: NASA.

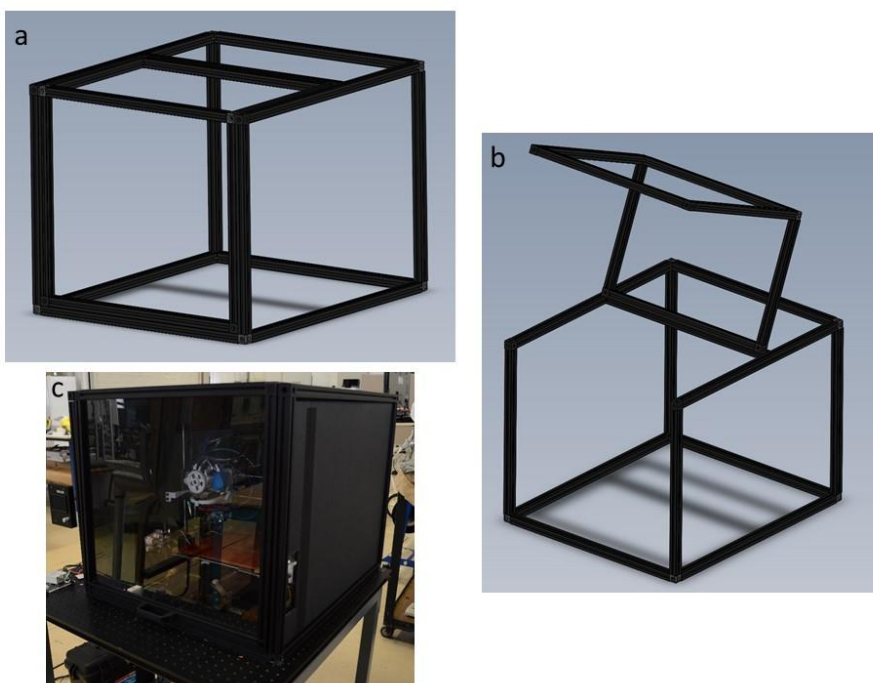


Figure 2: (a) 3D model of enclosure frame with door closed and (b) open. (c) Completed enclosure with front window. Image Credit: NASA.

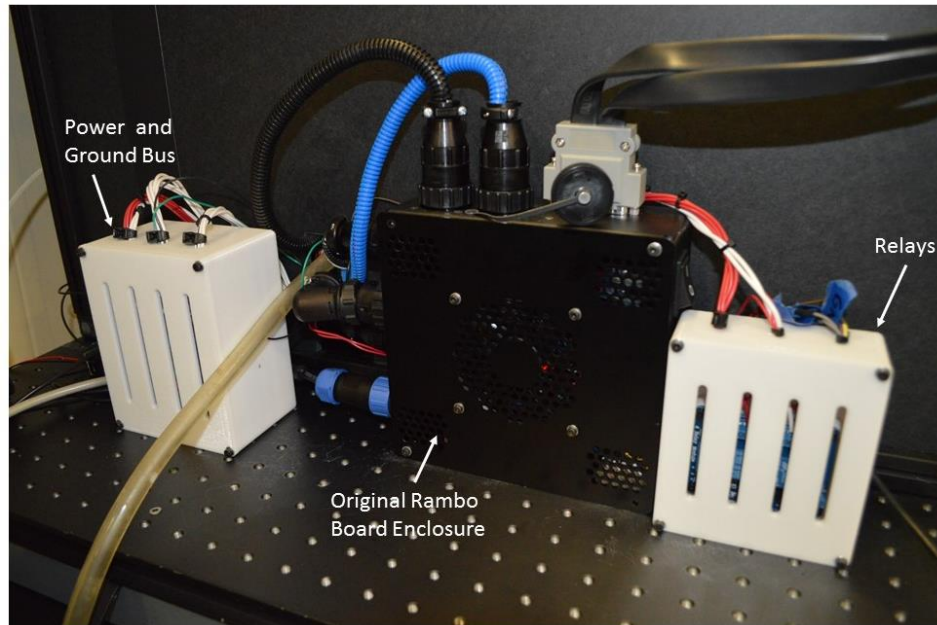


Figure 3: Image showing location of electronic components including IR heating lamp ground and power bus, relays, and Rambo electronics board. Image Credit: NASA.

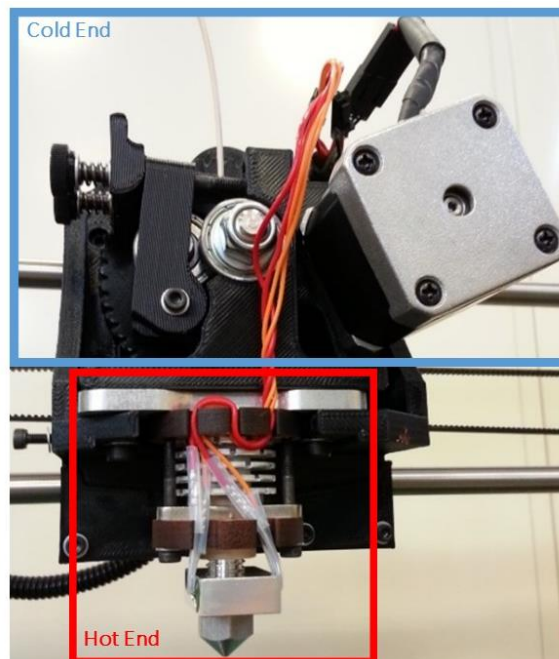


Figure 4: Stock FFF set-up showing the location of the hot and cold ends. Image Credit: NASA.

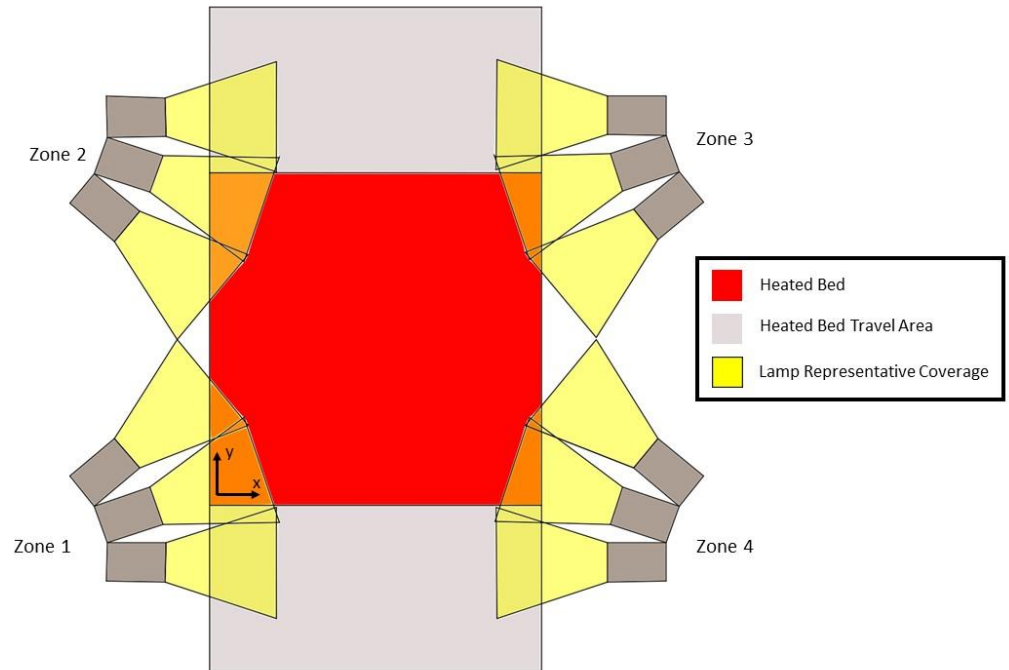


Figure 5: Layout of IR heating lamps with respect to the print bed. Image Credit: NASA.

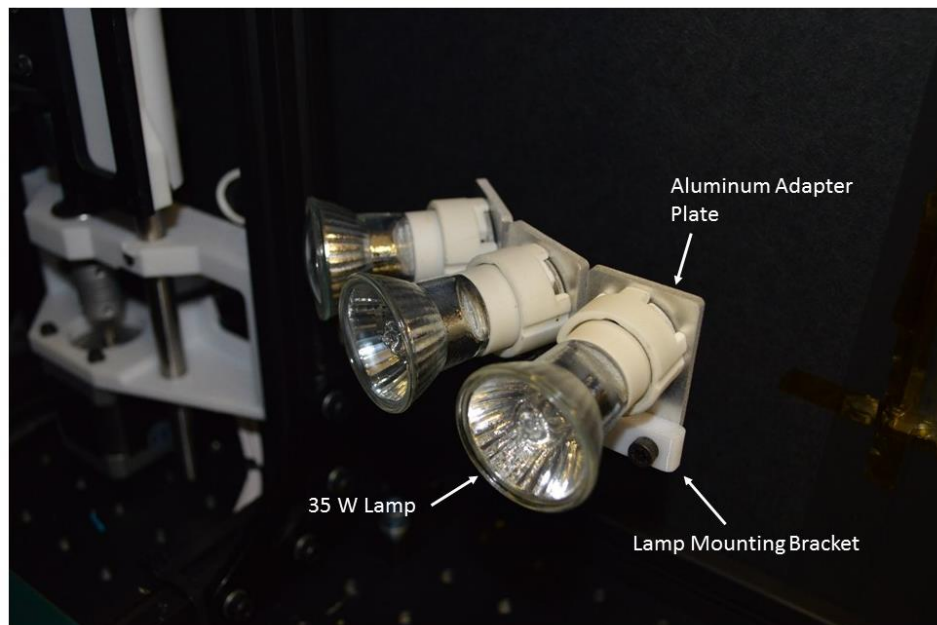


Figure 6: Image of IR heating lamp unit identifying the key components. Image Credit: NASA.

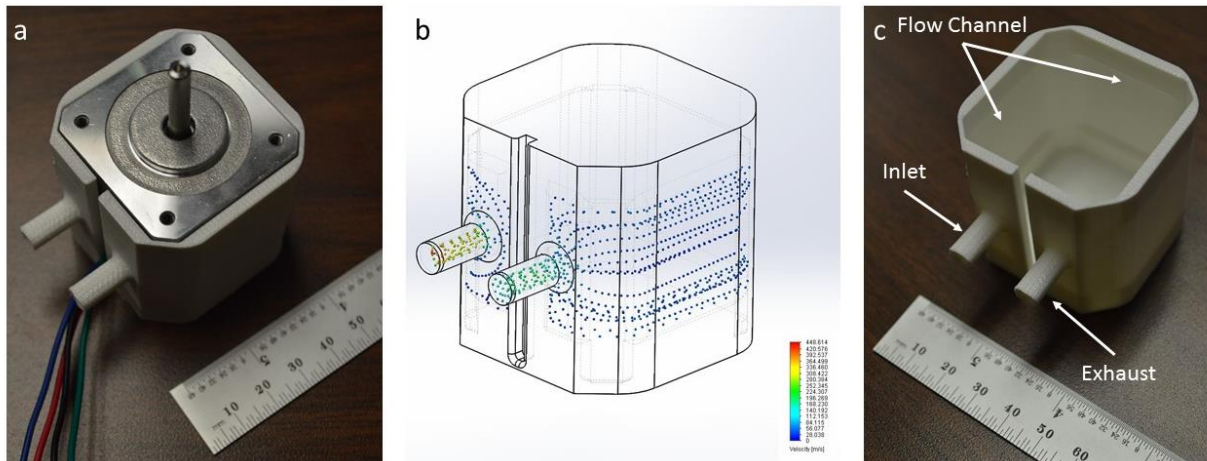


Figure 7: (a) Stepper motor cooling shroud installed on a NEMA 17 stepper motor. (b) Computational fluid dynamics model showing the airflow directed around the stepper motor. (c) Image identifying the key components of the stepper motor cooling shroud. Image Credit: NASA.

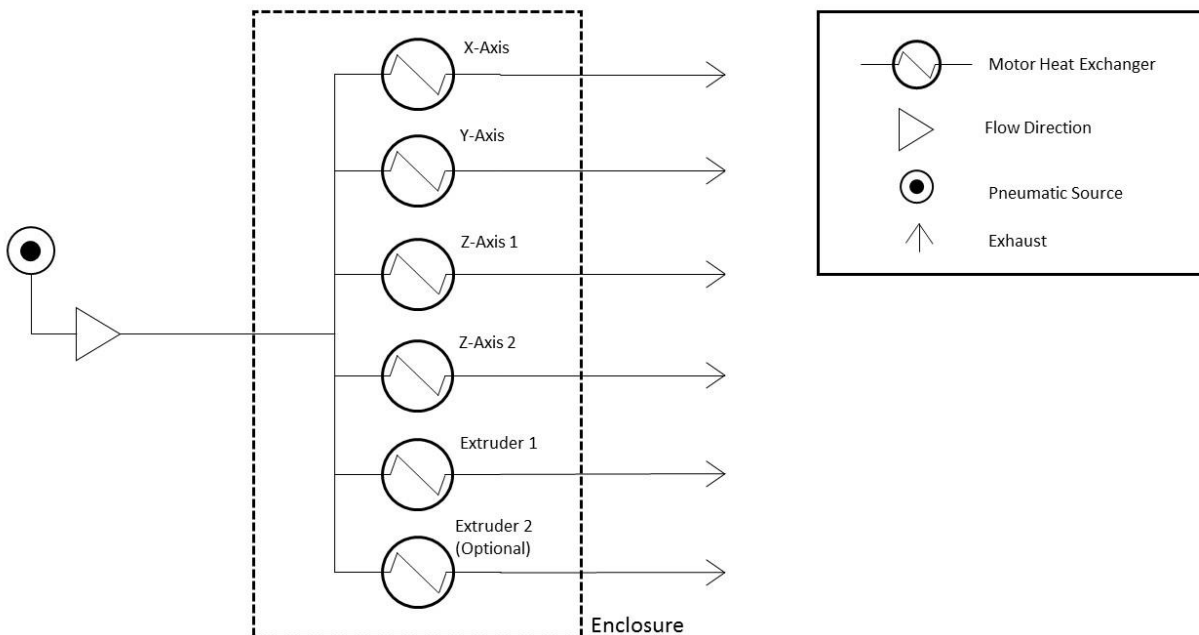


Figure 8: Pneumatic schematic of the stepper motor cooling system. Image Credit: NASA.

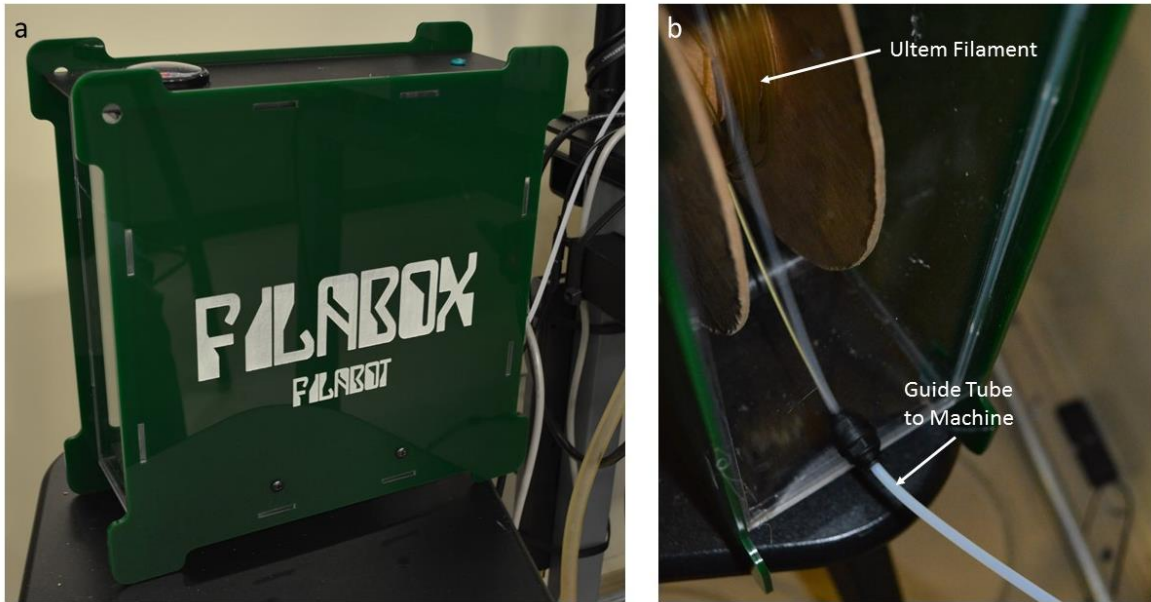


Figure 9: (a) Filament box used to store material during printing. (b) Image identifying Ultem® filament on a cardboard spool and guide tube from the filament box to the machine. Image Credit: NASA.

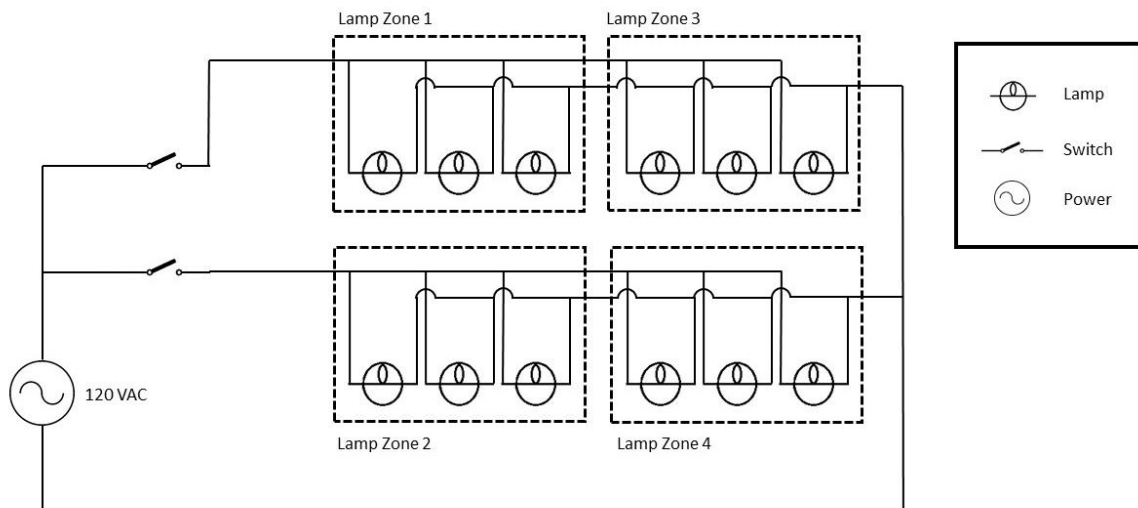


Figure 10: Electrical schematic of the IR heating lamp system. Image Credit: NASA.

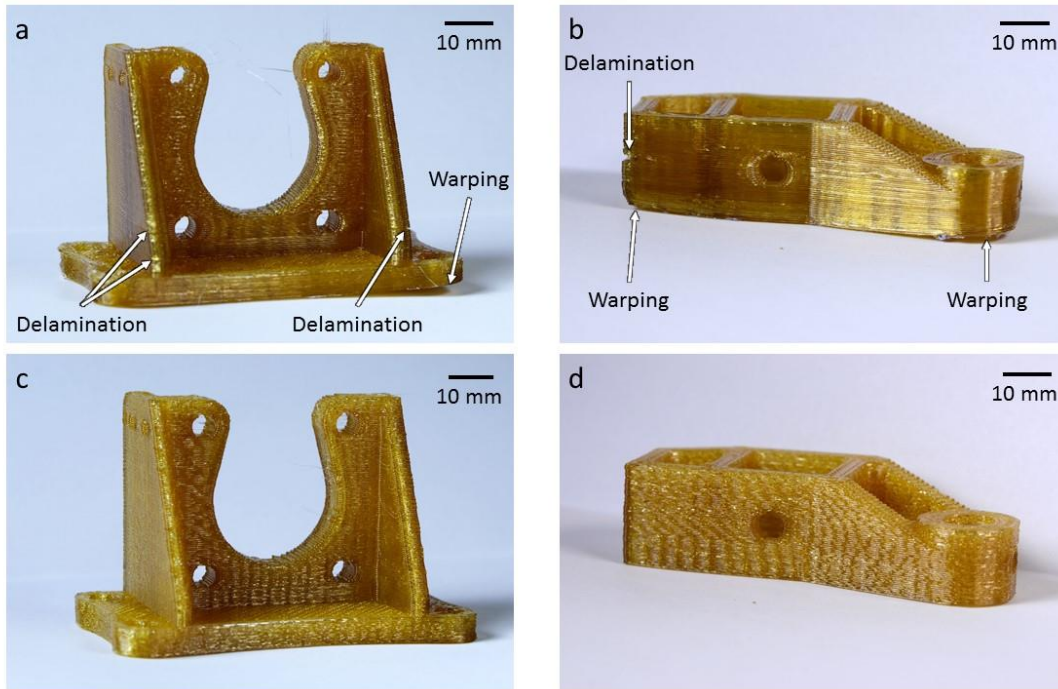


Figure 11: (a and b) Ultem® 1010 printed parts without heating lamps or other environmental controls with defects labeled. (c and d) Ultem® 1010 parts printed using IR heating lamps and enclosure. Image Credit: NASA.

Parameter	Value
Nozzle Temperature	345-375°C
Bed Temperature	155-200°C
Print Speed	up to 60 mm/s
Retraction	3 mm at 10 mm/s
Substrate Material	polyvinyl acetate (glue stick)

Table 1: Typical printing parameters used for Ultem® 1010.

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